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Eye Controlled Simulation of Scotoma Effects on the Retina

Annual / Final Report

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Scotoma simulation is useful for evaluating visual loss or disruption (eg from the aftereffects of accidental laser exposure or retinal isease) because it allows testing the size, position and shape of scotomas in normal subjects under controlled conditions. Human /e movements, made during visual performance tasks, were used to move an obscurant or mask to display areas corresponding to ie fovea. These real-time, eye controlled scotoma movements eliminated central vision and compelled the subjects to adapt by sing peripheral vision and eccentric fixation. Adaptation to the simulated scotomas was evaluated by measuring changes in the eye xation duration, saccade length and the eye position relative to instructed targets. Rapid development of eccentric eye positions, the :incipal means of compensating for the loss of central vision, showed that subjects are able to optimize the location of the scotoma lge by bringing it near a target. This maintains visual input to an area of retina outside of the scotoma with the highest receptor ensity. During and after adaptation, the presence of a simulated scotoma caused grossly distorted eye fixation patterns when ompared to normal fixation control. Abnormal patterns were reduced as subjects became more experienced with the simulated sual losses, but, there were persistent drift movements, dispersion of eye fixations and error fixations with the scotoma especially ider stress from accelerated pacing. Whether there is residual visual impairment after adaptation is dependent on the size of the :otoma, the length of the adaptation period and the visual demands of the task.

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Foreword

For the protection of human subjects the investigator has adhered to the policies of applicable federal law 45CFR46.

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Introduction

It is not surprising that central visual loss produces performance deficits and abnormal ocular movements since the central region of the retina, the macula, and its center, the fovea, have the highest density of light receptors. The fovea is used for finer visual tasks like reading text, threading a needle, checking a gauge, or searching for small targets. Foveal vision is distributed around the visual display in pauses called eye fixations at about three per second. Each fixation is followed by a flicking eye motion called a saccade or eye movement which delivers the fovea to a new visual field location. Central or foveal visual loss is associated with retinal diseases like macular degeneration or retinal detachments and with trauma from impact, blood vessel changes, or the light damage associated with accidental exposure to laser light. An absolute central scotoma refers to an a visual field area across the fovea that is completely unresponsive to light. If the damaged area is large enough or if the cell loss is absolute, visual search, reading text or instruments, or any fine detail work, becomes difficult or impossible. The advantage of the simulated scotoma method is that the damage area can be exactly defined or changed at will and maintained for longer study in complete safety, without any contact with the eye or exposure to strong light sources.

Simulated scotomata in normal human subjects as well as retinal or neurological lesions in patient populations produce strong adaptive responses and impairments in basic functions of the visual system. When artificial central scotomata are positioned across the fovea there is an increase in contrast sensitivity thresholds (1,2), a reduction in the motor component of convergence and divergence responses (3,4), and slowed reading and increased eye fixation duration (5). Recently, Bertera (6) used a simulated scotoma to examine the effects of loss of central vision on visual search time, eye fixation duration and saccade length. The results showed that a 10 or 20 minarc simulated foveal scotoma could increase both visual search time and eye fixation duration during search for acuity targets. Timberlake (7,8) using a scanning laser ophthalmoscope, identified acuity isopters around various visible abnormalities on the retina and these isopters were then related to the preferred retinal loci (PRL) used by patients for eccentric viewing. The PRLs were positioned near the scotoma boundary but not always in the area of best acuity. About 60% of patients show a stable PRL (9) within a 3x3 degree area; the larger the scotoma the more likely are multiple eccentric viewing locations.

This study was designed to further characterize adaptation to central visual loss by examining the development of eccentric eye fixation position, fixation duration changes and abnormal scanning patterns. Eccentric eye fixation or off center eye positioning relative to the target of interest was deemed of principal importance in analyzing adaptation. The working model for adaptation and visual loss (Figure 1) framing the present studies shows detection of visual loss and triggering eccentric fixations as the main mechanisms for overcoming deficits. If the subject has made an optimum adaptation to the loss of central vision, i.e. to the simulated scotoma, each change in eye position should place a target of interest on an area of working retina that is optimum for information acquisition (generally the area with the highest remaining acuity), eye position programming, or avoidance of errors. To fully compensate for central visual loss, both the attentional focus of the fovea and the motor control of the eye fixation response must be oriented to a peripheral retinal location (10). Uncompensated visual impairments or incomplete adaptation results in residual deficits.

Normally, when an observer is looking around a display with many targets, the focus of attention is taken to be the foveal fixation point at any moment. When looking with a scotoma, the

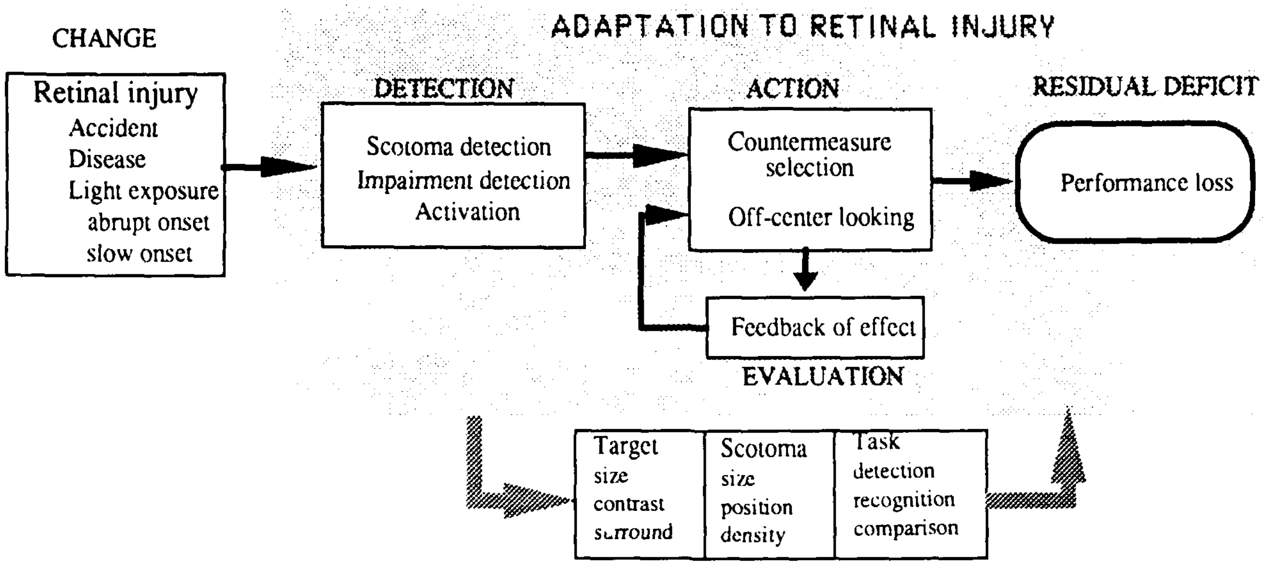

Figure 1. The model of adaptation to central visual loss begins with a change in the retinal receptors which lead to a detectable change in vision. A bright spot afterimage from light exposure or detectable loss of visual acuity leads to activation of adaptive processes. An experienced observer will begin off-center fixation in order to place the target of interest on an area of retina outside of the scotoma and monitors in some way whether this eccentric fixation strategy has a positive effect in reducing the scotoma impairment. With smaller targets, larger scotomas and more difficult tasks a residual visual deficit is likely.

attentional focus is uncertain; determining the peripheral location from which information is being extracted, around the edge of the scotoma, is ambiguous when a visual field has many targets. In some of the present studies this ambiguity was reduced by passing a stream of search elements through a limited number of display locations. For example, with a single search element stream location, a series of elements could be flashed successively, some of which were "targets" and some non-targets. The position of the scotoma relative to this information location could then be read continuously with much less ambiguity about the location of attention.

The simulation of a central scotoma employs feedback from high accuracy eye position sensors and requires close coupling with computer data acquisition and visual display control. Briefly, a subject's eye movements are used to move an artificial scotoma area around a display during visual search. At each fixation, the display area corresponding to the fovea is covered up. Different methods of scotoma simulation were evaluated to determine the practical significance of different levels of simulation fidelity in generating adaptation. Among these were the simulation fidelity criteria of the scotoma delay, scotoma image complexity and scotoma edge effects.

Simulator Systems

Five *scotoma simulator methods* were instrumented and tested with human subjects. They can be divided into optical overlay of scotoma image on task display, integrated raster with scotoma and task display in one, afterimage from bright white light flash and card edge simulator. Within the raster display methods are two different systems: prioritized buffer overlay (a hardware based method) and computed scotoma boundary with selective erasure of pixel data. The optical overlay method has been described previously (6). This report describes the raster display methods and the card edge simulator. The card edge simulator, a low fidelity, inexpensive simulation method, and a live video method for visible afterimage simulation are described later in a separate section.

A major problem in eye controlled simulation is accurately detecting and converting eye position coordinates into degradations of information at visual display regions corresponding to retinal scotoma boundaries. Horizontal and vertical analog eye position outputs from a Purkinje

tracker (11) were used to control the scotoma position. The analog outputs representing horizontal and vertical eye position were low pass filtered to limit an overshoot artifact characteristic of Purkinje trackers, digitized at 60 Hz to 200 Hz and stored. Placement of the scotoma was accurate to 5 minarc or better and accuracy was checked before and after about 80% of trials. The right eye was used to position the scotoma since the tracker only records from the right eye. Some subjects steadied their heads with a dental mould to insure accurate eye movement recordings. Calibration targets were used to relate eye position voltages from the Purkinje tracker to the display screen coordinates.

The visual search targets and the simulated scotoma were presented on a raster display. The use of raster technology instead of optical overlays

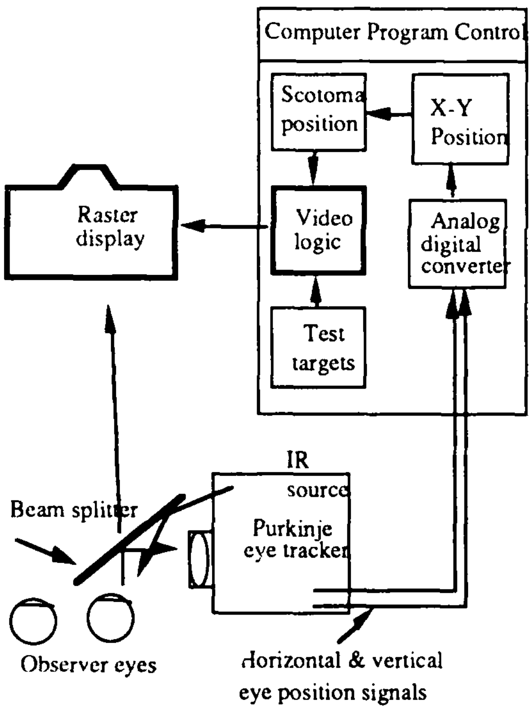

Figure 2. The scotoma simulation system is diagrammed with Purkinje Tracker, computer control elements and raster display. The subject's right eye movements are measured and the analog outputs for horizontal and vertical eye movements are fed to an analog to digital converter. Eye position relative to the raster display is then calculated from calibration values. The scotoma movements are accurate to within 5 minarc. The scotoma and visual display are integrated together within the same raster monitor.

(6) supported objectives to enlarge the scotoma size, to develop a scotoma with graded edges, to attempt to grade visibility through the scotoma, and to generate multiple scotoma patterns. An integrated scotoma and search display, and the fixation calibration targets were presented on raster displays where the maximum working area was 12 degrees wide placed 79 cm directly in front of the subject (Figure 2). The scotoma position was updated differently on various monitors at 60 Hz, 71 Hz, at a non-standard 180 Hz, or using an optical overlay with an oscilloscope at 250 Hz.

The non-standard 180 Hz video was developed to reduce the scotoma delay while taking advantage of the potential for image control within a raster system. It consisted of a modified ARTIST-16 graphic board along with a US Pixel black and white video monitor which were tuned to operate at 180 Hz. The higher frame rate was achieved by creating horizontal and vertical retrace signals after the output of about one third of the available 1024 X 1024 pixels, yielding a 512X400 display at 180 Hz. Vertical retrace was fed directly into the data acquisition system and the monitor for synchronization. The 180 Hz system employed distributed processing. A dedicated microprocessor converted analog eye position signals to digital and then passed parallel x-y coordinate data to a graphics processor which finally fed video and sync signals to the monitor.

Production of a smooth luminance contour from the scotoma edge inwards, in order to produce a graded edge scotoma, requires a set of accessible gray levels at the monitor and graphic controller. The commercially available 256 gray scale graphic controllers typically do not yield 256 visible gray levels. Calibrating gray levels is difficult also, but, prospects are good for wider ranges of useful gray levels. Programming algorithms for each scotoma location demand calculation of the luminance contour location of a target image relative to the scotoma center and then redrawing the image in the new luminance.

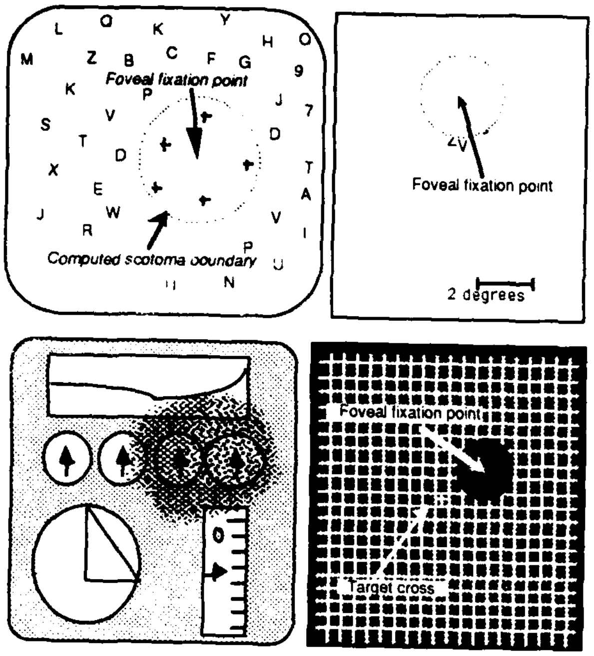

Figure 3. Scotoma types and search arrays showing obscuration methods with a simulated scotoma. Replacement of target image with a place holding cross maintains spatial location cues but obliterates identity (upper left). Blank field with crowded search area increases lateral masking effects (uper right). Relative simulated scotoma obscuring abstract instrument panel (lower left). Highly visible scotoma is outlined by obscuring a grid pattern while subject attempts to maintain target in clear view (lower right).

The scotoma boundaries (Figure 3) were calculated after each eye position sample and any displayed imagery within the scotoma boundary was masked or erased. Both visible and invisible scotoma edges were used. The displays used in these studies employed rasters with a white background and black foreground, the normal relation for text on paper. The display resolution was 1.7 minarc per pixel horizontal and vertical. The contrast was approximately 95%. The approximate luminance of the background was 1.9- 3.0 cd/m^2 and the foreground was 0.7-1.0 cd/m^2 depending on screen position.

Scotoma delay and scotoma image complexity characteristics are dependent on the simulated scotoma generation methods. The scotoma delay is the time taken to cover, obscure, or degrade the scotoma area of the display after the eye has moved to it. A long delay between eye movement and the updating of the scotoma position makes the display imagery easily visible, depending on the contrast between the scotoma and display image. Delays less than 16 or 32 msec between eye movement and scotoma movement are not found in commercially available video raster displays. A zero delay, the ideal, is only possible in a case of true retinal lesion or with an afterimage from strong light sources. The scotoma delays evaluated in the simulators in this project ranged from 5-16 msec. Scotoma image complexity relates to both the size, complexity of shape, pattern (multiple or single) and edge density gradient of the scotoma image. Higher degrees of scotoma image complexity are possible with longer scotoma delays and it is the different values in delay versus image complexity that are used to make the necessary compromises in the design of a specific study.

Procedures

Earlier work employed scattered search arrays or matrix arrays with 25 to 100 search elements which did not allow discrimination of well positioned eccentric fixations to one search element from error fixations to another search

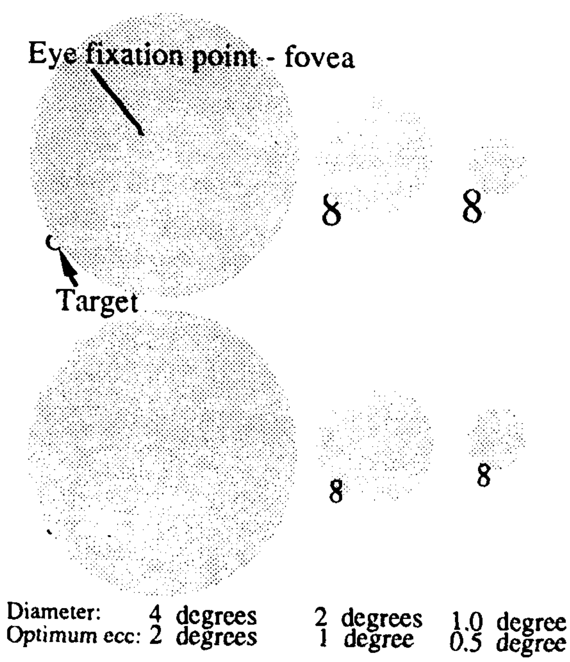

Figure 4. Scotoma sizes and targets (some partially obscured by scotoma boundary) are shown in relative size and in the preferred viewing position. The optimum eccentricity, or the degree of off center gaze, required to expose the target outside of the retinal scotoma is approximately the radius of the scotoma.

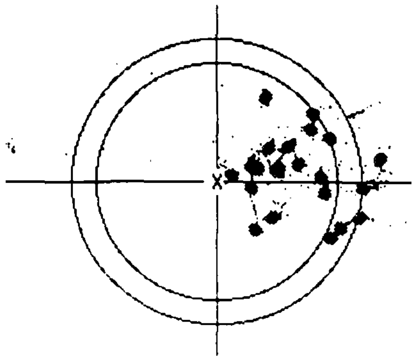

Figure 5. Error fixations are positioned within the boundary of a 120 min scotoma and obscure the target. After practice the saccade pattern is positioned outside of the circle indicating that the subject positioned the fovea at eccentric positions to allow a view of the target in peripheral vision.

element. In order to overcome this problem, search elements were presented in a serial, superimposed stream. For most of the work, streams of targets were presented from 1 to 5 locations around the display. The subjects were instructed to search for the occurrence of a target element and push a button on target recognition. Four search element sizes were tested from 10-20 minarc. Most of the serial streams were presented at the rate of 2 or 4 elements per second.

A target character disappeared, was replaced, or reduced in contrast when the scotoma boundary passed over it. Three scotoma sizes were compared for most of the presentations: 4, 2 and 1 degree in diameter (Figure 4), circularly symmetric and centered on the fovea. A minimum of 5-7 trials, consisting of 1200-2000 eye position samples, were presented for each scotoma size and target size combination, with most experimental conditions receiving 8 to 50 repetitions.

The x-y eye position samples along with the associated eye fixation durations were stored on computer disk. The samples were analyzed for the presence of fixations (typical criterion: dwell >100 msec within 10 minarc area), fixation dispersion around the targets, eye fixation duration, and saccade length. Error fixations, where the scotoma boundary crossed the target, were counted (Figure 5), and drift eye movements were examined for direction and velocity (Figure 6). Data were eliminated from the analysis if there were any large head movements, track losses or blinks.

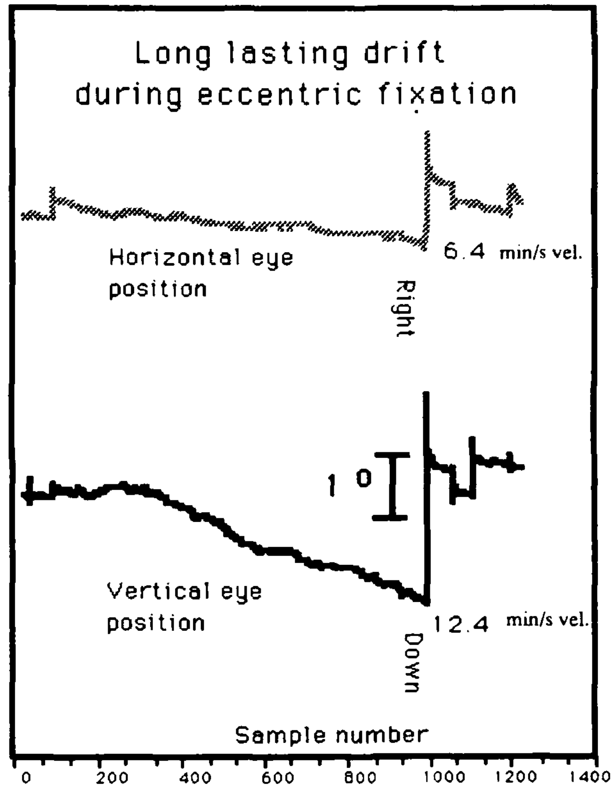

Figure 6. As fixations increased in duration there were more opportunities for the emergence of drift. Shown is long lasting centrifugal drift down and to the right (away) from the target. Drift velocity is not always consistent and some epochs where the eye slows down (eg around sample 600) may be considered a brief eye fixation, depending on criteria.

Designs and Results

Scattered target search showed increasing impairment with scotoma size.

Major vertical as well as horizontal eye scanning patterns were required with a scattered field of alphanumeric stimuli, 20 minarc wide and separated by an average of 1.5 degrees. A central obscurant was stabilized in real time around the fixation point using eye position measurements while 5 normal subjects searched for a target letter within an array of non-targets. Widening central scotomata were simulated with central obscurants of 0.3 to 3.0 degrees. Within the circularly symmetric visually obscured area, search elements were substituted with position holding crosses.

Widening the central scotoma increased the eye fixation duration and the search time (Figure 7). Fixation duration increased sharply from 242 msec to 340 msec as the scotoma size increased from 0.3 to 3.0 degrees with the sharpest increase from 0.3 to about 1.0 degree. The increasing trend in fixation duration was significant (F 1,20 = 6.20, $P<.05$). The longer fixation durations for the central scotomata may result from longer latency for information acquisition due to reduced peripheral resolu-

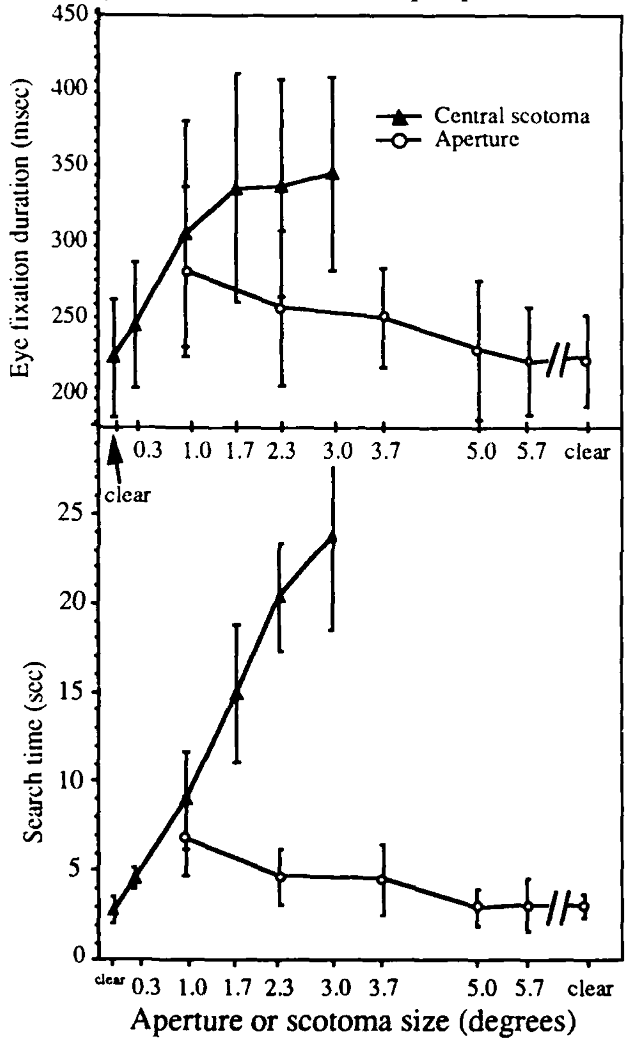

Figure 7. Search time and fixation duration increase with scotoma size; and to a lesser degree with more restrictive apertures. Fixation duration increases for scotomas and increasingly restrictive apertures demonstrates the generality of fixation duration adaptations. Standard error in brackets.

tion or longer time required for saccade programming because more accurate scotoma positioning is required as the scotoma grows in size. Increasing

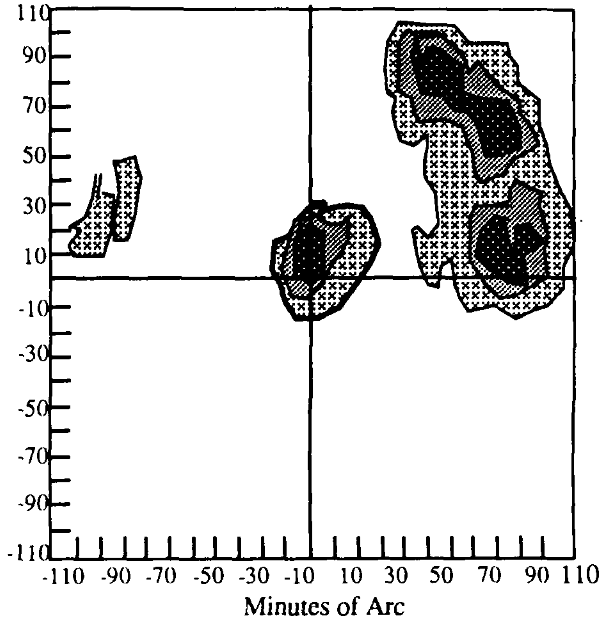

Figure 8. Composite topographical mapping of eye position samples for six subjects. The subjects attempted to keep a central target cross (located at intersection of lines) in clear as poss :e view for a total of about 300 sec with a 2.5 degree simulated scotoma across their fovea. An asymmetry is obvious in the scatter of eye positions which were freely chosen by these naive subjects. All subjects claimed that the upper right fixation position "felt" easier than anywhere else. *Clusters of eye positions near the* center represent the most common error: fixating the target with the scotoma.

scotoma size was also associated with steadily increasing search time scores from 4.4 to 24 seconds. The increasing trend in search time was significant from the 0.3 to the 3.0 degree scotoma (F 1,20 = 77.56, $P<.01$).

Static target viewing showed consistent asymmetries in preferred viewing position.

A circularly symmetric simulated scotoma of 2.6 degrees was stabilized on the fovea of 6 normal observers while they attempted to maintain a target in clear view. The subjects were naive and were free to view the target in any way they chose. In a free viewing condition, a series of 10-30 scotoma trials were presented lasting approximately 30 seconds per trial (16 msec delay). This was done to assess the immediate adaptation effects to the scotoma because pilot work had shown that eccentric eye control developed quickly. The subjects

were told to position their eye so that the central cross was "as clear as possible." The instructions did not indicate where they should look or how the subjects should do the task. The target size remained constant and the subjects tried only to maintain a subjective impression of image quality with their eccentric fixations. Cumulated fixation

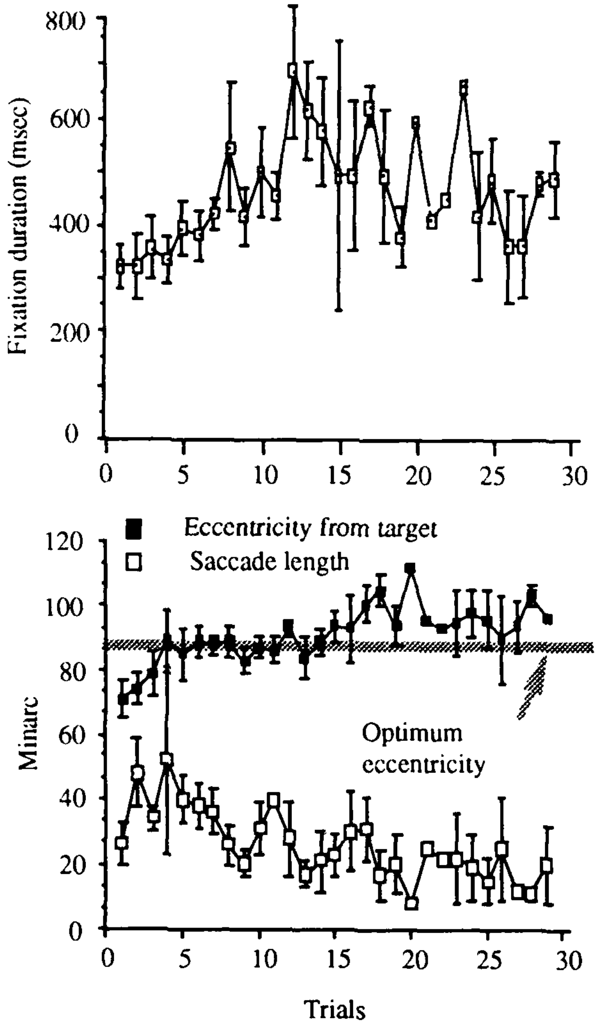

Figure 9. Average eccentricity form the target increased to an optimum level during early practice and after about trial 15 became more variable probably due to increased exploratory eye movements. Fixation duration follows this trend suggesting improved fixation stability. Shorter saccade lengths over trials suggests more precise fixation positions. Standard errors in brackets.

positions showed that the edge of the scotoma was positioned next to the target and that mean eccentricity was optimum (Figure 8). All subjects reported that they found an upper right position relative to the target easier to maintain as an eccentric vantage point and fixation maps showed that the majority of fixations were located there. Eccentric eye positioning developed within 2 minutes of viewing time with most subjects' (Figure 9). Fixation durations became longer during initial eccentric viewing practice indicating rapid improvements in fixation stability. Later durations were more variable probably due to subjects exploratory activity. In a subsequent condition a variety of viewing positions were tested for eccentric viewing stability, eccentricity and fixation duration. Although the upper right fixation position was generally more stable and more accurate than most of the other clock positions, the group means for fixation duration, saccade length and bivariate area were not significantly different among the instructed eccentric viewing positions.

Scotoma size changes did not alter preferred viewing point but interrupted drift.

A central field restriction boundary, circularly symmetric around the fixation point, was computed for each change of eye fixation position (7 msec scotoma delay). The 5 subjects were given approximately 20 trials with scotomata of 0.3, 1.0.

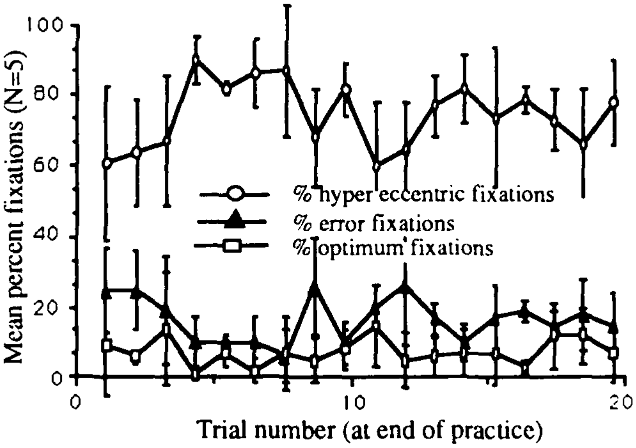

Figure 10. The percent of fixations which landed in three zones relative to the target. The error fixations landed close enough to the target so that the scotoma boundary covered the target. The optimum fixations were as close to the target as possible without covering it (defined as 0.2 of the scotoma radius). There were fewer optimum fixations than errors probably because of the accuracy demanded. The majority of the fixations were adequate to uncover the target but were positioned farther away from the target (hypereccentric) lowering the acuity, based on receptor density. Standard error in brackets.

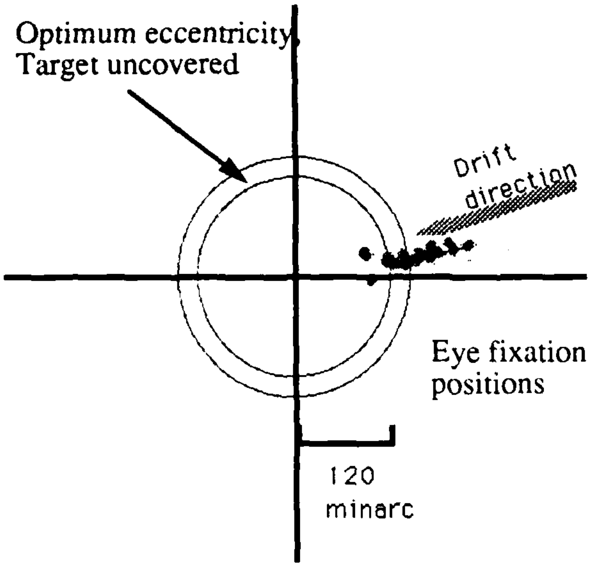

Figure 11. Centripetal drift with drift termination as the scotoma boundary crosses the target (located at center). Drift movements could be interrupted by a change in scotoma size, target size, instructing the subject or when the subject voluntarily moves the eccentric viewing position (eg from upper right to upper left). Drift was more likely as fixation durations became longer after a period of initial practice. Concentrated fixation clusters and drift appear to be mutually incompatible alternatives for establishing an eccentric viewing position for target monitoring.

2.0, 4.0 and 8.0 degrees. The subjects were instructed to move their eyes anyway they chose in order to make a stream of digits as clear as possible and to push the button on recognizing a target number . The serial stream of targets were presented at the rate of 2 or 3 per second. All the subjects again chose the upper right display position relative to the target as their preferred eccentric viewing position. The adaptation process was rapid for eccentric fixations but the subjects continued to make error fixations with the scotoma region on the target even after eccentric viewing stabilized (Figure 10). **In a second condition the subjects were instructed to attempt to maintain the "best position" they had found in experiment 1 in order to "see as many target digits as possible."** All subjects showed drift eye movements after an initial period of adaptation where error saccades were minimized. The drift movements ranged from 20 to 60 minarc/s and were a significant portion of the total viewing time, averaging 58%. All the subjects showed periods exclusively of drift patterns taking the form of jerk nystagmus (including a fast return saccade) which brought the scotoma edge near an optimum position to the target (Figure 11). Only one subject showed consistent centrifugal drift (away from the target), the rest of the subjects showed drift vectors either in centripetal or oblique directions.

Long training showed drift movements come and go depending on conditions.

Extended practice was given to 4 subjects with separate sessions on 4 days, each session lasting approximately 2 hours. The subjects maintained their PRL without instructions. Several sizes of scotomata and targets were applied randomly. The presence of drift, error fixations and PRL was assessed at the points of change for scotomata and target sizes. The following pattern emerged in all subjects: initial series of error fixations, the development of eccentric viewing positions, rapid selection of a PRL, reduction in error

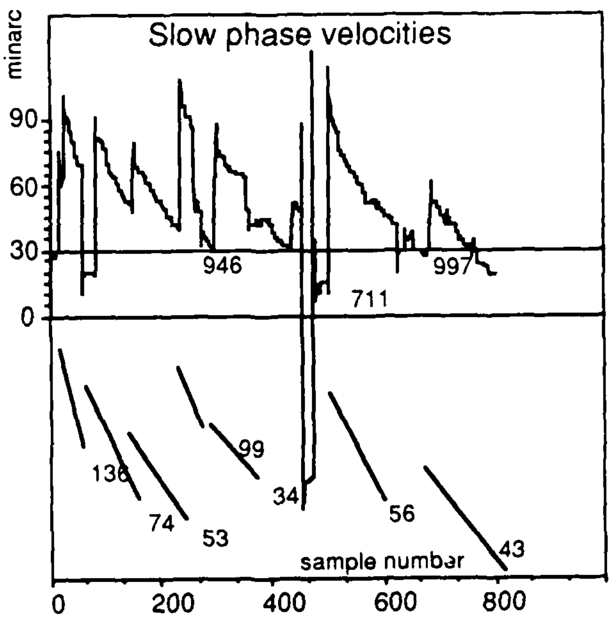

Figure 12. Horizontal eye drift with termination at the scotoma boundary. The drift appears under voluntary control and may be used to limit error fixations where the target is covered by the scotoma area. The velocity of drift is from 20 to 80 minarc/s, compared with some fast phase saccade velocities at around 1000 min/s. A higher drift velocity was typical early in the trial.

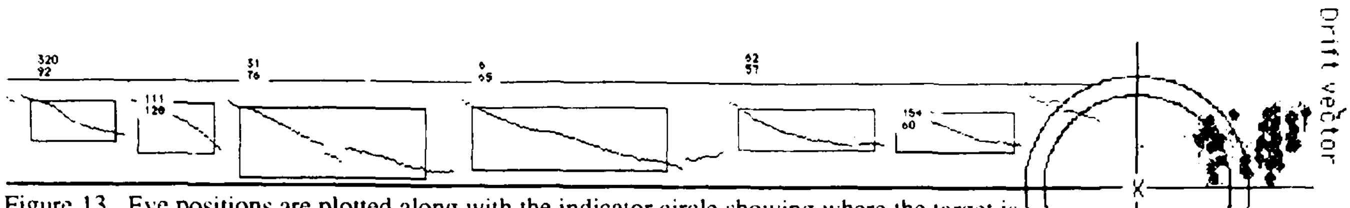

Figure 13. Eye positions are plotted along with the indicator circle showing where the target is obscured by the scotoma (inner circle). The vertical jerk nystagmus pattern outside of the indicator circle was repeated over many trials. The distribution of other fixations inside the circle are error saccades and may be associated with retesting the distance from target to scotoma edge. The trace shows the vertical eye position output with designators around the nystagmus pattern. H & V velocities (min/s) are at upper left.

fixations, the emergence of drift eye movements, most with nystagmic beats (Figure 12), interruption of drift with any change in conditions. The subjects were consistent in the positioning of the nystagmus pattern (for example, Figure 13); the drift track defines the PRL. After practice many cases of strategic drift termination were found. Where there was drift towards the target, the drift movement was terminated within about 10 minarc of the scotoma border (Figure 14). The drift pattern may serve to control error fixations. Extraneous noise, auditory feedback of saccade velocity, increasing or decreasing target size, increasing scotoma size, instructions to "hold your eye still now", all served to completely eliminate drift movements, even when subjects were drifting over 60% of the total time. After longer practice it should be pointed out that the subjects sometimes voluntarily moved their PRL to a different position on the scotoma boundary and the drift tracks sometimes changed as well (Figure 15).

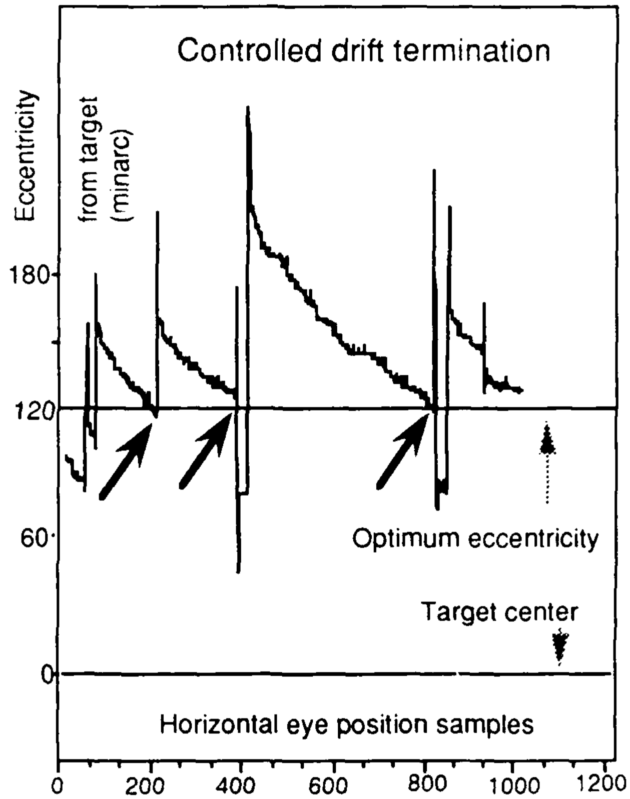

Figure 14. Repeated termination of drift as the scotoma boundary approaches the target (barbed arrows) generates a jerk nystagmus pattern. To avoid covering the target the subject must estimate the distance from fovea to target or from scotoma edge to target, or, the subject may wait for the drift to cover the target and then use the target disappearance as feedback signal for a saccade. Whether distance estimation, feedback or a combination of both operate to control eccentric viewing, there are still error saccades but they are too short to bring the fovea near the target. Drift may limit error saccades and fixations.

Scotoma edge visibility.

Scotoma edge detecting is important for optimum eccentric positioning. Edge encroachment on the target is necessary occasionally to verify the size of the scotoma. Also, some subjects may initially adapt with a PRL too far from the target to take advantage of maximum acuity. Three conditions were analyzed to test edge visibility effects: a relative scotoma, a background grid to make the scotoma edge visible, and a sizing procedure with a large scotoma for adaptation followed by a sudden shift to a small scotoma.

In the relative scotoma condition the elements within the boundary were replaced by a distorted remnant or a reduced contrast image (relative scotoma). This replacement procedure maintained visual information about the spatial location of a static target while reducing its visibility. This relative (less severe) scotoma reduced

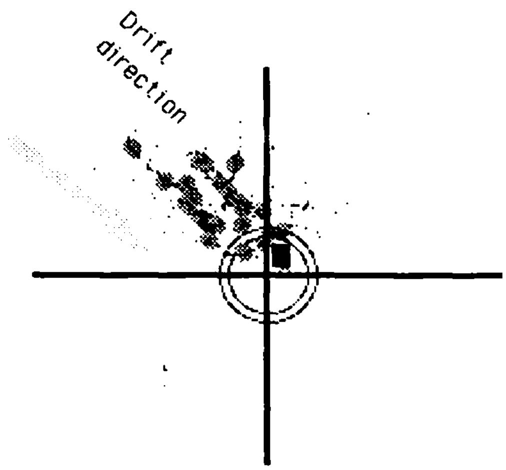

Figure 15. A centripetal drift pattern defines the preferred viewing position using a 30 min scotoma. Note the termination of drift near the scotoma boundary. This also illustrates the voluntary control of the viewing position since this trial is a reversal of the upper right position which this subject had previously maintained for many trials.

drift frequency, increased fixation duration and improved stability. Adaptation trials (20 each) were given to 5 subjects with and without a distinct background grid which outlined the edge of the scotoma. At each eye position change the full extent of the scotoma (0.5 and 2.5 degree, symmetric around the fovea) was visible as the grid and fixation target were obscured under its area. In the no grid condition the scotoma was invisible until the scotoma boundary crossed over the target. Some subjects claimed they looked around more; experimenting with the eye controlled image in the scotoma-visible condition. Stability was not significantly better in the scotoma-visible condition or with the 0.5 degree scotoma size. A series of 20 trials were also presented with a 2 and 4 degree scotoma to 3 subjects followed by a series of trials with a 30 minarc scotoma which would allow much closer positioning of the scotoma edge to the target. The subjects (who had good eccentric viewing position and stability and a strong PRL) did not adjust their eccentric fixation locus as scotoma size decreased when the scotoma edge was invisible (Figure 16). Instructions that the scotoma had decreased in size, however, produced an immediate adaptive response in which the subjects ranged the scotoma edge with a series of progressive error fixations and re-established their PRL. The strong PRL, a sign of rapid adaptation, does not supply feedback about a decreasing size scotoma when the scotoma edges are not visible. Flexibility may require periodic errors in order to recheck the invisible scotoma edge distance.

Imitative training was effective in eccentric viewing but not fixation duration or drift.

The scanning patterns of experienced observers were copied to video tape using 15 second intervals of the searching and monitoring task. The training recording consisted of the search condition requiring maintenance of eccentric fixations for the 20 minarc wide stream. The 20 repetitions were slowed down 4X to improve visibility. After the demonstration, the "training subjects" were given the same conditions and asked to mimic the kind of looking behavior they had just watched in the recordings. Some of the looking patterns were unusually inefficient and difficult but the subjects were still well able to reproduce them. The subjects made typical error fixations and nystagmus-like drift movements.

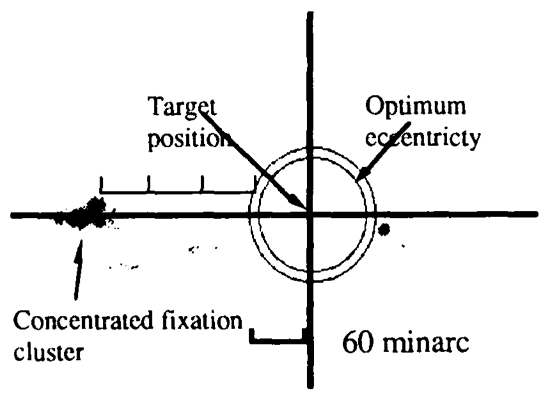

Figure 16. This subject's eye positions show paradoxical eccentric fixations -- while the scotoma is only 60 min radius the main fixation cluster is approximately 3 times farther from the target than necessary. This subject was given a larger scotoma on previous trials and had very stable fixation position. When the scotoma became smaller the subject did not adapt because no feedback indicated that the eccentric fixation position should be adjusted inwards to optimize the viewing position. Verbal instructions that the scotoma is smaller produce fast correction to paradoxical eccentric fixation.

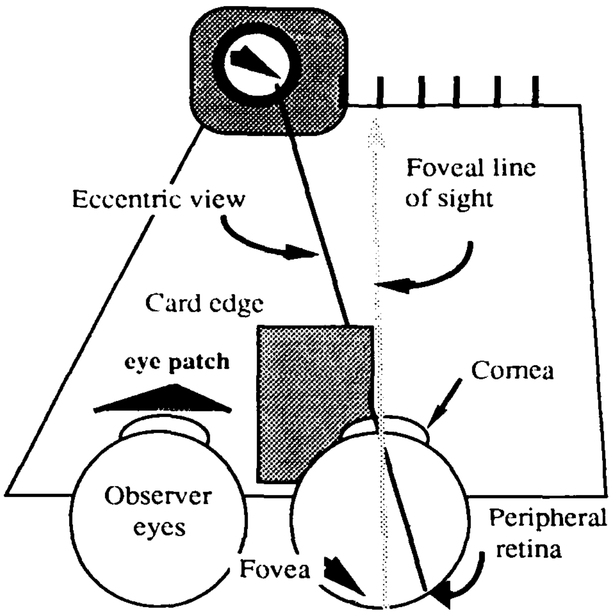

Figure 17. The simple simulator consists of a card edge held vertically in front of one eye with the other eye covered. The edge is positioned in the center of the pupil as close to the eyeball as possible -- brushing the eye lashes is close enough. While keeping the card edge and head still, the subject looks away from the target center in small steps until the target appears in peripheral vision. Looking back and forth between the target and an off-center point makes the target disappear and reappear alternately, simulating the effect of a central scotoma

Scotoma overlay on live video.

Live video was used as a background image for an optical overlay of a simulated brightspot afterimage. An optical pathway was added to the subject's view with a large beam splitter similar in general design to a previous method (6). The brightspot, 0.3 to 2.0 degree diameter circularly symmetric about the fovea, was adjusted so that the underlying image was obscured completely. Documentary films were used to present aircraft and vehicle movements. Multiple scotomata were programmed into the eye control brightspot and served to obscure larger areas of the visual image. Eye movement data was recorded but patterns were probably compromised by the relatively low luminance video image required to maintain good eye position tracking. The method appears to have potential for presenting a wide range of dynamic stimuli with simulated scotomata.

Simple simulator.

The card edge simulator is a card held vertically in front of one eye with the other eye covered. The edge is positioned in the center of the pupil as close to the eyeball as possible — brushing the eye lashes is close enough. The subject looks straight ahead at a clock face, instrument panel or any other defined target and positions the card edge so that the target is just obscured (Figure 17). While keeping the card edge and head still, the subject now looks away from the target center in small steps until the target reappears in peripheral vision. Looking back and forth between the target and the off-center point makes the target disappear and reappear alternately. The subject was presented a series of visual signals on a computer display and was required to read the letters, figures or words into a microphone. The recorded responses were analyzed for accuracy. A sample of the eye fixations showed error fixations and drift movements after adaptation which appear to be similar to scotoma impairment with an eye controlled scotoma. Of course, the advantage in cost and ease of use make this method worth pursuing further as a training and demonstration aid for central visual loss and the value of eccentric eye positioning to regain visual function. The head restraint was poorer than typical for very good eye movement recordings perhaps because more head movements were induced by the much larger scotoma.

Accelerated pacing caused breakdown of compensation.

In earlier tests with arrays of scattered targets, asking subjects to increase the pace of their eye fixations reduced their compensation (more errors of fixation). Modulation of saccade pace, that is, voluntarily shortening or lengthening eye fixation duration was used as the independent variable. The 3 subjects were required to look back and forth between two search locations with a 30, 60 or 120 minarc diameter scotoma while attempt-

ing to fixate using an eccentric viewing position (i.e. land their saccades off center). Then the subjects were asked to pace themselves more slowly in one condition and more quickly in another condition. The accelerated rate produced more fixation errors and the average eccentricity was pushed away from the target more as the pace went from slow to fast for the larger scotomata (Figure 18). The eccentricity was poorer by 6 minarc for the 30 minarc scotoma, 14 minarc for the 60 minarc scotoma, and 31 minarc for the 120 minarc scotoma. The subjects were able to maintain the side of their eccentric fixation at all paces, i.e. the eccentric viewing position was consistently on the right side or the left side.

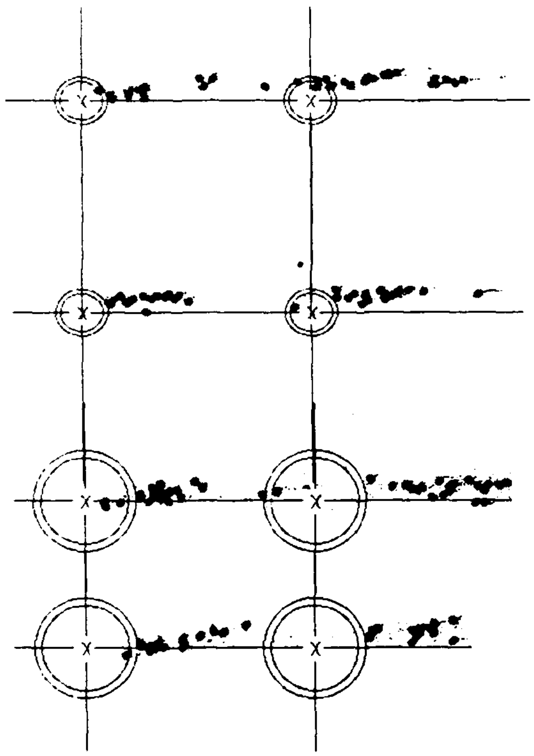

Figure 18. Scanning pattern between two target locations with a 30 and 60 minarc scotoma with the faster pace in the upper traces. Increasing the pace tends to spread out the eccentric fixation pattern. Some subjects attempted to fixate in between the targets in order to achieve a better vantage point. No drift movements were noted (except for a slight downward nystagmus) since drift and saccades are mutually incompatible when looking back and forth.

Discussion/Conclusions

Research in our laboratory with simulated scotomata has shown that the periphery may be used as a substitute for central retinal functions if the task demands are not too great, for example, if only target detection is required, or, if the scotoma is not too large. The subjects engage in a period of adaptation in which they learn rapidly to make eccentric or off center eye fixations. Subjects appear to choose fairly fixed eye positions relative to the target when they lose central vision. These eccentric eye positions keep the scotoma edge off the target most of the time and seem to be optimized. That is, the edge of the scotoma is about 10 minarc away from the target. Such adaptation in eccentric fixation position control can take place within minutes. Rapid adaptation has also been documented in the duration of eye fixations or the dwell time of the eye at each fixation position. Eye fixation duration increases by as much as 15% even for relatively small scotomata and some saccade lengths are shortened. The number of error fixations which is initially very high also decreases rapidly as adaptation proceeds. Error fixations position the scotoma so that it covers the target. Error fixation position can range from the scotoma center on the target to the scotoma edge just covering the target. Both error types can mask the target completely and bring the flow of visual information to zero.

Under favorable conditions of scotoma size, target size and task, eccentric fixations and fixation duration changes may fully compensate for central visual loss, for example, for the subject with a small scotoma, a large target, a simple detection task, or high contrast. However, there are usually residual deficits after the adaptation period either in the visually guided performance or a residual abnormality in the eye movements used to achieve the adaptation. Large scotomata produce worse deficits than smaller ones. Fine or small targets are more difficult to see with a scotoma than large targets. Recognition tasks are more impaired than detection because recognition generally requires finer detail or more visual information.

A consistent preferred viewing position developed rapidly in these studies and was resistant to change due to task conditions. Positioning the scotoma should be optimized so that a candidate target is just outside of the scotoma area; as near to the fovea as possible to maximize acuity, particularly for targets with fine detail. The use of consistent or strategic eccentric looking may be an important source of compensation for central visual loss. Consistency may allow less effort in maintaining compensation or in adding value to early adaptation. The reason for holding eccentric fixation to the right and up from the target remains a mystery, but it may have implications for understanding or augmenting adaptation. While there were some indications that the stability of gaze was better in this area, the reason for the lateral preference is not clear. Several possibilities may be considered to explain this strong asymmetry. First, some motor habit, like a reading scan may bias the fixation position. Better stability or control may be achieved if the eccentric vantage point inhibits most error which was fixating the target with the scotomatous fovea. It could be speculated that the upper right position was preferred in free viewing and tended to produce less errors in instructed looking because reading habits are left to right in English. Eye movements going in the opposite direction, from right to left, may be better inhibited or less likely.

However, it is now clear that consistency in fixation position will not allow optimum adaptation if scotoma size is reduced during the adaptation period (See Figure 16). Periodic error in the form of fixations on or near the target are necessary to retest the scotoma size during recovery from temporary visual loss. A shrinking scotoma area due to retinal cell recovery must be probed with wasted fixations to determine the extent of dysfunctional retina. This implies that a subject who establishes a stable eccentric viewing position will show poorer performance as the scotoma size shrinks than a less skilled fixator who makes occasional error fixations. This assumes that both subjects would move their eccentric viewing position closer to the fovea if they had feedback that retinal function had returned to a previously unresponsive area. By contrast, in a patient population with expanding retinal disease, the fixation control system must gradually adapt by pushing the "motor center" farther from the fovea, e.g. as a macular degeneration increases in size.

Feedback of failures to detect targets might serve to stimulate the production of more strategies and yield better performance. Larger scotomata or very difficult tasks in which there is a good deal of poor performance may maintain a flexibility in the eccentric fixation positioning which might lead to better performance after a larger set of positioning and information processing strategies had been tried as compensation for visual loss. Alternatively, an incorrect switch from an optimum strategy because of a low threshold for discarding a strategy would have to be avoided. The level of feedback about the success of a particular adaptive strategy, such as eccentric fixation, and the expectation for success will determine the future of the adaptive responses. If the subject is successful immediately or if the task is easy then adaptation may not go very far. Importantly, if the critical signal set is of low frequency (intermittent) then there may be no feedback as to incorrectness until a critical target is missed. Low levels of feedback would also be present with a scotoma and background that were perceived as very similar, i.e. without edges to indicate the scotoma position or the disappearance of display imagery.

The level of feedback about the scotoma edge, contributing to the triggering and maintenance of adaptation, is a function of the relationships between the scotoma, the background and the foreground images. For example, a dark scotoma with a distinctive edge seen on a lighter background (assuming the background does not fill in) would supply relatively more feedback about the scotoma position (and eye position). On the other hand, if there is little or no background the absolute dark scotoma will be invisible to the subject until the boundary crosses a target and obscures it. Less feedback about eye and scotoma position means less information is available for the development of adaptive eye behavior. This makes training rather important since some critical tasks may not supply sufficient feedback to motivate adaptive

processes, even in an aware subject.

It is clear that subjects can be rapidly trained to imitate the eccentric viewing behavior of a model whether the model is created with instructions, video recording or paper sketch. Further, other forms of real time scotoma simulation such as the card edge simulator appear to have value because of low cost and ease of use. These low level simulations of central scotoma in real time may be used for training and demonstrating the beneficial effects of regaining some vision by using off-center looking or eccentric vision. For example, the card edge method can supply long term practice at eccentric fixation skills. It is inexpensive, reliable, portable and very safe. This can be compared with the afterimage method of training eccentric fixation used in rehabilitation of low vision patients. The afterimage method has no scotoma delay, but there is a limited persistence within safety limits, limited repeatability, and it is limited to a positive overlay.

The largest effect on eccentric fixation control found in the present series of studies was produced by the emergence of strong drift movement patterns whose drift tracks create a new definition of the eccentric area of best view. The effect of this eccentric viewing area is large since the drift tracks may be as wide as a scotoma radius or more and up to 50% of the viewing time may be spent while the eye is drifting in (for the case of centripetal drift) from a less than optimum acuity position or while the eye is making a return saccade. While drift movements under scotoma conditions have been observed by other experimenters (9,12), identification of the generating or releasing conditions remains a problem.

Monitoring multiple target locations adds complexity to the adaptation process because a saccade offset must be programmed into each saccade. Monitoring a single target requires saccades only to correct error fixations or drift movements. Making repeated accurate saccades of one degree or more using an eccentric viewing position is difficult to learn and recovering the accuracy of foveal fixation is probably not achievable under pressured conditions. Even after practice saccades placed the scotoma boundary 2 or 3 times farther away than comparable eccentric fixations achieved when saccades were not required (monitoring a single target location). The visual performance impairment accounted for by inaccurate eccentric eye positioning when making saccades may be an example of a residual deficit.

The residual deficit, the leftover impairment from the adaptation process, is dependent on task difficulty and task sensitivity. Evaluating the difference in impairment between two conditions requires repeated measurements over time and this will coincide with the development of adaptation. In order to study a factor of eccentric eye control without experimental confounding it is necessary to use a task with some degree of stability in the level of impairment in either oculomotor or performance measures. A stable residual deficit can be used as a test measure for scotoma or stimulus characteristics, but, using a residual deficit model may not be equally explanatory of the development of adaptation, especially if the time course is rapid, as seen in several simulated scotoma experiments. Further research is now being applied to characterization of the development of adaptation and the nature of residual performance deficits.

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